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Evaluating the development of carbon capture and storage technologies in the United States

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ABSTRACT

Carbon capture and storage (CCS) is seen as an important solution to solve the twin challenge of reducing GHG emissions, while utilizing fossil fuel reserves to meet future energy requirements. In this study an innovation systems perspective is applied to review the development of CCS technologies in the US between 2000 and 2009 and to come up with policy recommendations for technology managers that wish to accelerate the deployment of CCS. The analysis describes the successful built-up of an innovation system around CCS and pinpoints the key determinants for this achievement. However, the evaluation of the system's performance also indicates that America's leading role in the development of CCS should not be taken for granted. It shows that the large CCS R&D networks, as well as the extensive CCS knowledge base, which have been accumulated over the past decade, have not yet been valorized by entrepreneurs to explore the market for integrated CCS concepts linked to power generation. Therefore, it is argued that the build-up of the innovation system has entered a critical phase that is decisive for a further thriving development of CCS technologies in the US. This study provides a clear understanding of the current barriers to the technology's future deployment and outlines a policy strategy that (1) stimulates technological learning; (2) facilitates collaboration and coordination in CCS actor networks; (3) creates financial and market incentives for the technology; and (4) provides supportive regulation and sound communication on CCS.

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1. Introduction

Carbon dioxide (CO_2) emissions from fossil fuel based power generation contributes close to 40% of the total CO_2 emissions in the US in 2008. This number is expected to increase by 2% in 2030 [1]. To balance the demand of both reducing greenhouse gas (GHG) emissions and assuring a reliable energy supply, the scientific community, industry, and political leaders have identified carbon capture and storage (CCS) as a viable technological option to address both issues [2]. CCS entails separating CO_2 from industrial or energy-related point sources, and then injecting it into underground geologic reservoirs for permanent storage (such as depleted hydrocarbon fields and deep saline aquifers). First assessments indicated that the US might have a storage capacity of more than 1000 times the annual US CO_2 emissions [3].

The US Department of Energy (DOE) is taking a leading role in the advancement of CCS technologies. Through its Carbon Sequestration Program – managed by the office of fossil energy and implemented by the National Energy Technology Laboratory (NETL) – DOE is supporting the development of a large variety of CCS technologies since 2003 [4]. There are three main components to the US CCS activities: core R&D related to CCS; deployment through the Regional Carbon Sequestration Partnerships (RCSPs); and major demonstration projects through the Clean Coal Power Initiative and FutureGen efforts.

Despite a successful start of DOE's CCS support programs, the deployment of large-scale CCS projects suffered severe setbacks in 2007 and 2008. High profile projects were cancelled or postponed, including NRG's Huntley coal gasification plan with CCS in New York State; Hydrogen Energy's zero emissions power plant in Carson, California; and most (in)famously, the desire by US-DOE to restructure the financial arrangements of the FutureGen project in Illinois, because of escalating cost estimates [5]. The rethinking of these projects – which often have been portrayed as the gateway to a cleaner and secure energy future – outlines that new technologies, like CCS, are often not able to negotiate the various market and institutional barriers that confronts them [6]. It shows that substantial investments in technological R&D and demonstration do not necessarily lead to successful innovations. Given the prominent role that CCS is now taking in global attempts to attain climate mitigation goals [7], it is essential to gain more insight in the CCS innovation process to investigate whether handholds for successful support strategies can be developed.

Failures in the market and new insights obtained from innovation theory deepened our understanding of innovation processes. Scholars such as Nelson and Winter [8], Freeman [9], Lundvall [10] and Kline and Rosenberg [11] emphasised that organisations are not innovating in isolation but in the context of an innovation system. The basic idea of an innovation system is that the innovation process is strongly influenced by a network of actors that are developing, advocating or opposing the technology and by an institutional infrastructure that legitimizes, regulates and standardizes the new technology [12]. A well-performing innovation system accelerate technological development and increases the success chances of new technology, while a poorly functioning innovation system hampers technological innovation [13].

Over the past few years further progress has been made in determining key processes that need to take place in innovation systems in order to perform well (see, e.g. Hekkert et al. [14]; Bergek et al. [15]). These system functions – e.g. knowledge diffusion and market creation – are decisive processes that foster the shaping and development of a technology [16]. In earlier empirical work the functions approach has been used effectively to deliver explanations for the success or failure of technological trajectories of sustainable energy technologies in various countries [17–22]. Furthermore, their fulfillment can be assessed to derive policy strategies for supporting a specific technology [23–25].

This study applies the functions of innovation systems framework to evaluate the performance of the US CCS innovation system. We aim to provide insights into the relations between the historical growth of the innovation system and the system's current performance. Furthermore, we will derive policy and management strategies for technology managers that wish to accelerate the development and deployment of CCS in the US.

2. Theoretical framework

From the 1980s onwards, innovation system studies have pointed out the influence of the social system on innovative performance. Different approaches exist – for an extended review, see Carlsson et al. [26] and Lundvall et al. [27] – but all studies point to the *structure* of the innovation system as the explanatory basis. The structure of an innovation system consists of actors, their networks, institutions, and also incorporates technological features [28]. We follow Carlsson and Stankiewicz [12] in defining the US CCS innovation system as those structural elements that directly support (or reject) the development and (future) diffusion of CCS technologies in the US.

According to this definition the formation and growth of a technological innovation system can be described by changes in its main components. For example, actors, such as firms looking to exploit the benefits of CCS technologies, enter the system and interact with other organization through cooperation or competition. Actors are organized in networks and networks often interrelate: e.g. industry networks influencing political networks in order to enforce institutional changes. In turn, institutions, such as public resource endowments or technological standards, influence the information flows between (networks of) actors and thereby foster or hamper technological advancement [29].

Yet, whereas it is known that structures need to be built-up, the performance of a certain structure cannot be assessed very easily since many different structures can lead to similar outcomes. Hence, there is no optimal system configuration that identifies the precise attributes of actors, networks and institutions in a well-performing innovation system [25]. Therefore, we present a framework outlining seven key processes – here labeled as 'functions of innovation systems' – which have a direct impact on the development and diffusion of new technologies. The premise is that the components of the system should be

Table 1
Functions of technological innovation systems [14].

F1. Entrepreneurial activity	At the core of any innovation system are the entrepreneurs. These risk takers perform the innovative (pre-)commercial experiments, seeing and exploiting business opportunities.
F2. Knowledge development	Technology R&D are prerequisites for innovations, creating variety in technological options and breakthrough technologies.
F3. Knowledge diffusion	This is important in a strict R&D setting, but especially in a heterogeneous context where R&D meets government and market.
F4. Guidance of the search	This function represents the selection process that is necessary to facilitate a convergence in technology development, involving policy targets and expectations about technological options.
F5. Market creation	This function comprehends formation of new (niche) market by creating temporary competitive advantage through favorable tax regimes, consumption quotas, or other public policy activities.
F6. Resource mobilization	Financial and human resources are necessary inputs for all innovative activities, and can be enacted through, e.g. investments by venture capitalists or through governmental support.
F7. Creation of legitimacy	The introduction of new technologies often lead to resistance from established actors, or society. Advocacy coalitions can counteract this inertia and lobby for compliance with legislation/institutions.

successfully arranged to bring about an optimal fulfillment of seven system functions, each of which covers a particular aspect of technological innovation (see Table 1 for definitions).

The seven system functions are considered a suitable set of criteria for the performance assessment of an emerging innovation system structure [15]. To some extent, system functions need to be realized simultaneously, since they can complement, or reinforce each other [28], but an innovation system may very well collapse due to the absence of a single system function. For example, Kamp [30] has shown that the Dutch wind energy innovation system was well developed in the 1980s but collapsed as the result from the absence of knowledge exchange between the emerging turbine industry and users, the latter being mainly energy companies. So, there may be particular functions that drive or block the growth of a specific technological innovation system. The analytical framework that is outlined below further elucidates this.

3. Research design and methods

This analytical framework is based on the assumption that policy interventions directed at stimulating a successful build-up of the US CCS innovation system should focus on improving functions that are considered to be ‘weak’. In order to determine such an intervention strategy, the historical built-up of the innovation system structure needs to be assessed first. Subsequently, the performance of this emergent system structure must be evaluated using the functions of innovation systems. Both analytical parts are discussed below.

3.1. Part 1: innovation system structure

The first step is to analyze the formation and growth of the innovation system structure in terms of institutions, actor networks and technological advancement. We mapped the build up of an institutional infrastructure by conducting an extensive literature review of scientific as well as ‘grey literature’ (e.g. professional journals and policy papers) on regulatory issues regarding CCS.

We applied social network analysis to identify the actor networks involved in the US CCS innovation system and how the relations between actors change over time.

The social network approach assumes that the structure of linkages among actors can favor or impede the diffusion of innovations in the system [31]. It identifies the network structure as a major factor to help the system evolve [32]. Two dimensions of social networks are positively related to the successful build-up of an innovation system, network size and network connectivity. The size of the network is determined based on three measures: number of actors, the size of largest component – i.e. connected parts of the network – and average distance between actors in the network. The connectivity of the network is determined based on the average number of linkages per actor (mean degree) and the clustering coefficient, a measure to determine the existence of relative dense clusters in the network [33]. Social network analysis can also be performed on an actor level. The number of linkages of an actor (node degree) and its betweenness are centrality measures indicating the position of an actor in the network.

In this study, two actors are considered to be exchanging knowledge – and thus related – when they are involved in the same CCS project. This could be a cooperative R&D effort, a policy network, but also a commercial joint venture. In order to specify the relations between actors in the innovation system, a comprehensive project database has been constructed. The database contains over 150 CCS projects that have been carried out in the US between 2000 and 2008, involving more than 350 organisations. To create a network, an adjacency matrix is created. In this matrix, actors are placed at the heads of the columns and rows. If a link exists between actors, this is represented by a positive value in the cell. The adjacency matrices are then used in specialized network software to visualize the networks, i.e. Visone [34] and UCINET 6 [35].[1]

The most important sources of information for the construction of our CCS project database are the NETL ‘Carbon Sequestration Project Portfolio’s’ [37,38]. The data is complemented and verified using the CCS database of the IEA GHG R&D program [39] and the Fossil Research and Engineering Database of US-DOE [40]. Additional information has been gathered using various reports, project fact sheets and interviews with project managers.[2]

Besides the name of the actors involved in CCS projects, the following data has been recorded in order to specify the technological focus and advancement in the CCS knowledge base:

1. The organisational background of the actor (e.g. oil and gas industry or universities).
2. The technological focus of the project. Thereby we have distinguished between three categories: CO_2 capture, CO_2 storage, and other CCS areas, including CO_2 transportation, public acceptance and policy analysis. The capture projects are then subdivided into post-, pre-, and oxyfuel combustion; and in storage we distinguish three main types of geological reservoirs, namely saline aquifers, oil and gas fields (both depleted and producing) and coal seams.[3]
3. Each project is classified in terms of ‘distance to market’. A project is considered: (a) basic and applied R&D; (b) demonstration (early prototypes up to full-scale working devices); (c) pre-commercial (commercial-scale prototypes and integrated demonstration projects).

[1] For more information on Social Network Analysis and data setup we refer to the widely cited book of Wasserman and Faust [36].

[2] It is recognized by the authors, that some projects are developed exclusively with private funding and that information on these projects is not always available.

[3] Note that CCS projects can fall in multiple categories and that R&D projects related deep ocean CO_2 storage and CO_2 mineralization are not included in the database.

4. Finally, the start and end date, as well as the costs of the project are recorded in order to gain insight in distribution of costs among technological options over time.

3.2. Part 2: innovation system performance and system intervention

The second part of the analysis aims at ascertaining to what extent the functions of innovation systems are currently fulfilled by the components of the system. The data for this sub-analysis are collected by extensive literature review and by interviewing the main actors involved in the development of CCS in the US. Hereby we made use of a number of indicative questions that provide insight in the fulfillment of the functions (see Table 2). In total, 18 interviews have been conducted with senior representatives from industry, research, government and environmental groups. Also, within stakeholder groups variety was sought (e.g. researchers involved in both capture and storage technologies; representatives from natural resource companies as well as electric utilities; and policy makers at various government levels). With cross-referencing as well as external justification, the validity of the group of interviewees was guaranteed.

In order to assess system performance, we have the main actors in the system reflect upon the ongoing activities in the system and rate their level of satisfaction with the fulfillment of a particular system function. The interviewees have been asked to score the fulfillment of each system function on a 5 point Likert scale where 1 = very weak, 2 = weak, 3 is sufficient, 4 = good and 5 = very good. In this way, our results from the analysis of the system structure are triangulated with critical evaluations from experts who took part in shaping the technological trajectory for CCS in the US.

Based on the current performance of the system, it is possible to indicate drivers and barriers in terms of how the innovation system functions should develop so that system growth is stimulated. Therefore, the respondents have not only evaluated the current functioning of the innovation system, but also gave their view on what should be done to improve functions that are impeding a higher system performance. This provides the basis for intervention strategies that aim to accelerate the development and deployment of CCS in the US.

Table 2
Indicative questions that reflect the extent to which each function in the innovation system is fulfilled by the components of the system (see also [14,15]).

F1: Entrepreneurial activity
The number and the degree of variety in entrepreneurial experiments?
The number of different types of applications?
The breadth of technologies used and the character of the complementary technologies employed?
The number of new entrants and diversifying established firms?
F2: Knowledge creation
The number and degree of variety in RD&D projects?
The type of knowledge (scientific, applied, patents) that is created and by whom?
The competitive edge of the knowledge base?
The (mis)match between the supply of technical knowledge by universities and demand by industry?
F3: Knowledge diffusion
The amount and type of (inter) national collaborating between actors in the innovation system?
The kind of knowledge that is shared within these existing partnerships?
The amount, type and 'weight' of official gatherings (e.g. conferences, platforms) organized?
Configuration of actor networks (homo, or heterogeneous set of actors)?
F4: Guidance
Amount and type of visions and expectations about the technology?
Belief in growth potential?
Clarity about the demands of leading users?
Specific targets or regulations set by the government or industry?
F5: Market creation
What phase is the market in and what is its (domestic and export) potential?
Who are the users of the technology how is their demand articulated?
Institutional stimuli for market creation?
Uncertainties faced by potential project developers?
F6: Resource mobilization
Availability of human capital (through education, entrepreneurship or management)?
Availability of financial capital (seed and venture capital, government funds for RD&D)?
Availability of complementary assets (complementary products, services, network infrastructure)?
Level of satisfaction with the amount of resources?
F7: Legitimization
Public opinion towards the technology and how is the technology depicted in the media?
What are the main arguments of actors pro or against the deployment the technology?
Legitimacy to make investments in the technology?
Activity of lobby groups active in the innovation system (size and strength)?

4. The structure of the US CCS innovation system

The development and diffusion of technology can be seen as the outcome of the actions of actors that operate under a particular institutional infrastructure. We will now describe the formation and growth of the US CCS innovation system by changes in its structural building blocks, namely: (1) institutional infrastructure; (2) the network of actors; and (3) the technology.

4.1. Institutional infrastructure

Until 2009, climate change mitigation in the US has been primarily a technology-driven voluntary effort. Nevertheless, CCS has been an important consideration in US climate policy discussions as it is recognized as a possible solution to solve the twin challenge of reducing GHG emissions, while utilizing indigenous coal reserves to meet future energy requirements. Therefore, a number of proposals that involve GHG regulatory requirements and CCS have been considered in the US Congress and in individual States [41]. The proposed policy mechanisms to limit GHG emissions and stimulate the use of CCS vary widely. Carbon taxes, emissions performance standards (EPS), portfolio standards, cap-and-trade systems, direct subsidies, and indirect subsidies such as tax credits, have all been discussed, often in combination with each other [42]. See for example, the Clean Air Planning Act of 2003 [43], the Climate Stewardship and Innovation Act of 2007 [44], the Low Carbon Economy Act of 2007 [45], and the Lieberman-Warner Climate Security Act of 2008 [46]. However, it was not until June 2009 that the first climate legislation, known as the American Clean Energy and Security Act (ACES), was approved by the House of Representatives [47].

ACES will establish a cap-and-trade system for GHG emissions from all major emitting sectors including power producers. It requires a 17% emissions reduction by 2020 and over 80% by 2050 compared to 2005 levels. Furthermore, the Bill includes the implementation of emission performance standards (EPS) to prevent continued investment in high emitting power sources and ensure a level playing field for the utility sector. The ACES Act requires that all new coal plants permitted after 2020 must use CCS when they commence operations. Coal plants permitted between 2015 and 2020 that do not use CCS must retrofit CCS by no later than 2025 without federal financial assistance. Coal plants permitted between 2009 and 2015 lose eligibility for federal financial assistance if they do not retrofit CCS within 5 years after commencing operations. The federal financial assistance consists

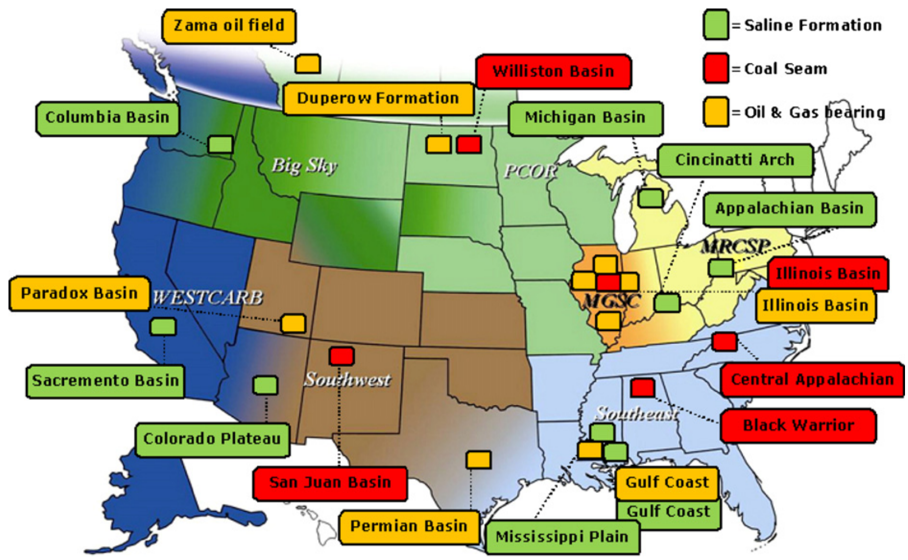


Fig. 1. Location of regional carbon sequestration partnerships validation phase geological field tests (see also [4,38,51,52]). Partnership abbreviations: Big Sky Carbon Sequestration Partnership (Big Sky); Midwest Geological Sequestration Consortium (MGSC); Midwest Regional Carbon Sequestration Partnership (MRCSP); Plains CO_2 Reduction Partnership (PCOR); Southeast Regional Carbon Sequestration Partnership (SECARB); Southwest Regional Partnership on Carbon Sequestration (SWP); West Coast Regional Carbon Sequestration Partnership (WESTCARB).

of direct cash payments up to USD 90 per tonne of captured CO_2 and the establishment of a Carbon Storage Research Corporation to be run by the Electric Power Research Institute. The Corporation would use funds collected through a feed-in tariff to issue grants – capped at USD 1 billion per year – for early commercial scale CCS demonstrations [47,48].

Despite the passage of ACES in the House, the future of the Act remains uncertain, as it faces both opposition and competing bills intended to address climate change in the Senate. For example, the Senate Energy and Natural Resources Committee passed the American Clean Energy Leadership Act in June 2009. This bill addresses several of the same energy issues addressed by ACES, but with a stronger emphasis on enhancing energy efficiency and increasing capitalization for clean energy projects, rather than mandatory emissions reduction [49]. These measures, as well as proposals from other Senate committees, will likely be combined to create the Senate counterpart to the ACES Act. If the Senate passes this combined bill, differences between the Senate and House bills would have to be reconciled, with the final bill passed by both houses, before the bill could be sent to President Obama and signed into law [50].

Even though an overarching climate legislations targeting CCS is not expected to be in place before 2010, the development of CCS has been key in US fossil fuel R&D programs for over a decade now. Next to the Clean Coal Power Initiative and FutureGen efforts, the Carbon Sequestration Program is the most comprehensive CCS R&D program in the US. The objective of this US-DOE sponsored program is to develop fossil fuel based power plants with over 90% CO_2 capture and 99% storage permanence, as well as less than a 10% increases in electricity costs by 2012 [51]. As part of the Program, DOE has formed a nationwide network of seven Regional Carbon Sequestration Partnerships (RCSPs). The RCSPs are public private partnerships that involve more than 350 organizations covering 42 states and four Canadian provinces. The RCSPs are tasked with determining the most suitable technologies, regulations, infrastructure and public outreach strategies for CCS in their areas of the country. Furthermore, the RCSPs project sites serve as field laboratories to test the core R&D technologies at scale and in real-world conditions, which in turn shapes the requirements for future R&D needs [4].

The RCSPs are being implemented in three phases. The objective of the first phase (2003–2005) is to collect data on CO_2 sources and sinks; and to identify the most promising storage opportunities taking infrastructural issues into account. After this 'characterization phase', the RCSPs started in 2005 with the implementation of 22 small-scale geologic field tests (see Fig. 1), whereby between 10 and 100 $ktCO_2$ has been injected at each project site. DOE has invested approximately USD 120 million into the development of field tests and industry is bearing a 40% cost share. The main results of this 'validation phase' (2005–2008) have been the validation of simulation modeling and the deployment of monitoring protocols. The lessons learned in the validation phase, which also relate to regulatory requirements and public engagement, are valuable for the final phase (2009–2017), whereby DOE is investing approximately USD 500 million into the development of large-scale CCS projects (>1 Mt/CO_2). The objective of this 'deployment phase' is to demonstrate that large volumes of CO_2 can be injected safely, permanently, and economically into geologic formations [52].

Next to the funding of national CCS projects, the US-DOE is working with the Department of State in several international consortia to plan and implement joint projects all over the globe, including the Asia-Pacific Partnership on Clean Development and Climate, the IEA GHG program and the Carbon Sequestration Leadership Forum (CSLF). The latter is an international ministerial-level, which is tasked with establishing a companion foundation of legislative, regulatory, administrative, and institutional practices that will ensure safe, verifiable CO_2 storage.

At the national level, it is recognized that CO_2 injection and storage can only be partly covered by existing Federal and State legislation on CO_2 for enhanced oil recovery (EOR), natural gas storage and acid gas disposal. Therefore, the US Environmental Protection Agency (EPA) proposed regulation for commercial-scale CO_2 storage under the Underground Injection Control (UIC) program [53]. The rule suggests a new UIC injection well class IV for CO_2 storage wells and includes standards for site characterization, well construction and operation, monitoring

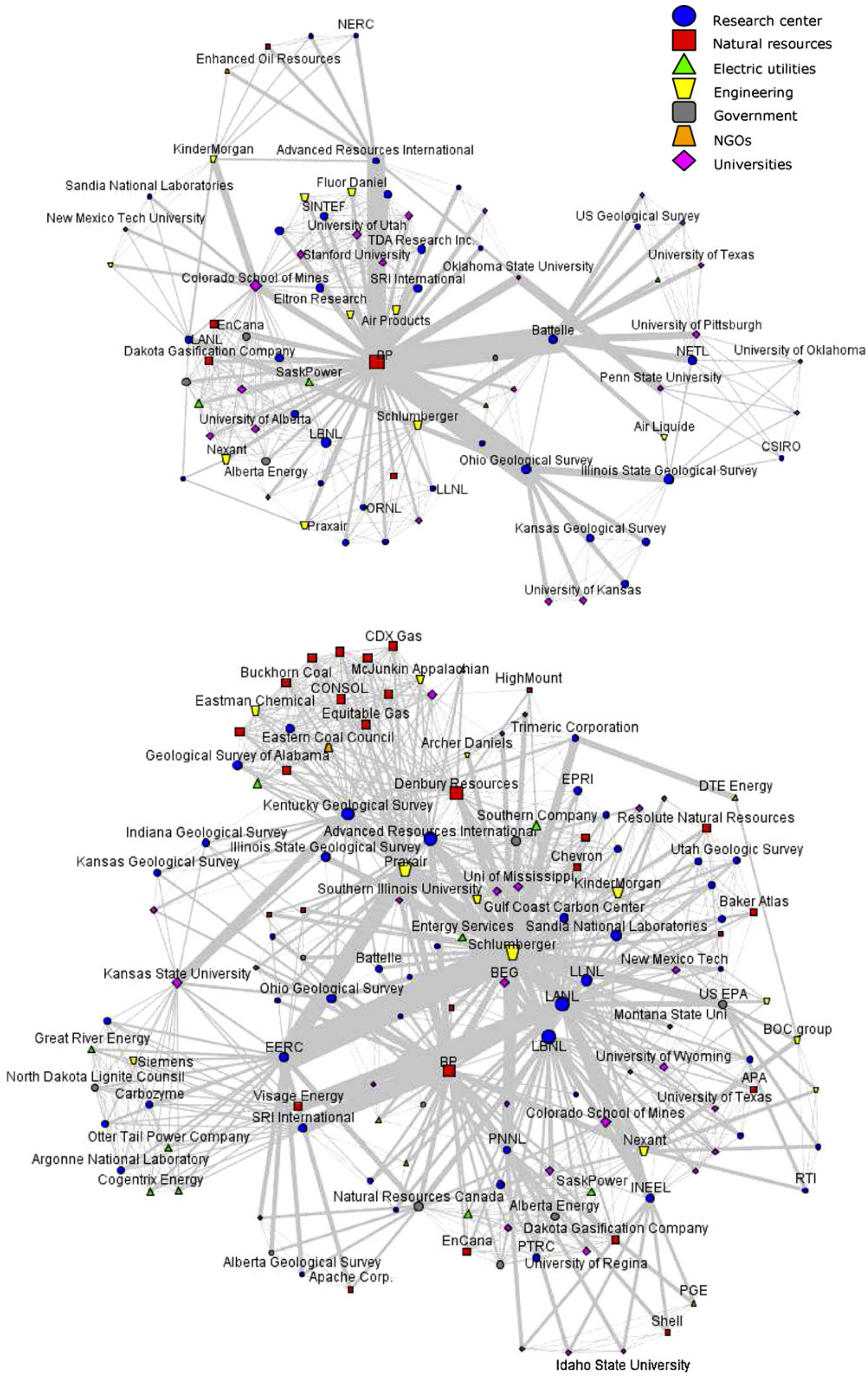


Fig. 2. Visualization of CCS actor networks between 2003–2005 (top) and 2006–2008 (bottom).

and post-closure care. In addition to the national regulators, several states, including Illinois, Kansas and Washington, are actively pursuing CCS through implementing regulations for geological CO_2 storage [5,54]. Moreover, the ACES Act requires the EPA, in consultation with the heads of other relevant state and federal agencies, to submit to Congress a comprehensive strategy to address the key legal and regulatory barriers to the large-scale deployment of CCS.

4.2. Actor networks

Both the increasing amount of funds available for CCS and the cooperative nature of CCS R&D programs, as well as the alignment of the regulatory environment with the technology, have positively influenced the growth of CCS networks in the US. Fig. 2 visualizes the US CCS network between 2003–2005 and 2006–2008; corresponding to the characterization and validation phases of

the DOE's Carbon Sequestration Program. In the visualized networks, the nodes are the actors and the edges are the result from cooperation in CCS projects. The network visualizes only actors that have five or more linkages.[4] The number of linkages (degree) determines the size of a node; the width of an edge is proportional to its betweenness. For example, in the characterization phase BP is positioned in the centre of the network with 51 linkages and the link between BP and Batelle obtains a relatively high betweenness value as it represents the shortest path length between the actors grouped around BP in the centre of the network (e.g. Sask power and the Colorado School of Mines) with the actors clustered in the periphery on the right side of the network (e.g. the Universities of Pittsburgh and Texas).

BP obtains its central position through its involvement in three large CCS projects (in terms of actors), namely Weyburn, Frio Brine and the CO_2 Capture Project (CCP). Until now, the Weyburn project and its related R&D program, is the only commercial-scale CCS project that has been carried out in North America. Since 2000, approximately 1–2 $MtCO_2$ is injected annually to enhance oil recovery from the Weyburn field in Saskatchewan, Canada. The CO_2 that is used in this project is a by-product from synthetic methane production at a coal gasification plant, located approximately 325 km south of Weyburn, in North Dakota (US). Several American actors are involved in the Weyburn EOR project; e.g. Dakota Gasification Company, Colorado School of Mines, Nexant and Lawrence Berkely National Laboratory (LBNL). These actors have the possibility to transfer the knowledge obtained within the Weyburn cluster (depicted on the left side of the network) with the actors involved the Frio project, depicted at the bottom. Frio Brine is the first project in the US whereby CO_2 is injected into high-permeability sandstone.

The CO_2 Catpure Project (CCP) is an international effort led by BP and co-funded by US-DOE. It includes R&D of advanced CO_2 separation and capture technologies in pre-, post- and oxy-combustion. Through its involvement in the CCP, BP is the linking node between the major capture and storage clusters in the network's centre. Some smaller projects that can be identified in the periphery of the network are: the NatCarb project (bottom right), which includes all the major geological surveys in order to identify possible CO_2 sinks; the CO_2 storage test project at Strata's West Pearl Queen oil reservoir in New Mexico (top left); and the COAL-Seq consortium, which is lead by Advanced Resources International (top), and focuses on R&D of CO_2 storage in deep unmineable coal seams and various ECBM processes.[5]

Even though we apply equal time spans for the division of the data and the amount of active projects remains constant between both periods (around 100), the size of the network more than doubles from 89 to 192 unique actors in the second period. The latter can be explained by the implementation of more than 20 small-scale storage field tests that involve a relatively large amount of actors per project. The national laboratories, which play an important role in these projects, can now be found in the core of the network. For example, LBNL has got 67 linkages, which is more than double the amount compared to the first period. Also Schlumberger is heavily involved in the partnership projects and therefore obtained the most central position in the network in the second period with 69 linkages; thereby outnumbering other companies like BP, Praxair and Denbury Resources, which all have about 50 linkages in the network.

Due to the considerable size of the field tests, several of them can be identified in the network visualization of the validation phase. For example, SECARB's Central Appalachian Coal Seam Project in Virginia can be found in the upper left of the network. There are more than 20 partners involved in this project, including CNX Gas, Buckhorn Coal, Virginia Tech and Consol Energy. It is notable that other actors involved in smaller coal storage field tests, like the Black Warrior project in Alabama and the Illinois Basin 'Huff 'n Puff' field test are also positioned at the top of the network. This indicates that actors like Denbury Resources, EPRI and Acher Daniels Midland, seek cooperation based on their technological competences, instead of geographical proximity, or organizational background. This notion is strengthened by the clustering of actors involved in oil-bearing and aquifer storage projects right of the centre of the network. For example, Kinder Morgan and Baker Atlas are involved in the Permian Basin EOR project in Texas; and the national laboratories (i.e. LLNL, LANL, and LBNL) are collaborating in the 'Teapot Dome' EOR project in Wyoming. However, the actors involved in the PCORPs' projects that are located in Canada – i.e. the Zama, Fort Nelson and Weyburn EOR projects – are clustered together at the bottom of the network.

On the left side of the network we find the only distinguishable capture clusters. Together with 14 partners Carbozyme Inc. is developing scalable enzyme-based post-combustion capture technology to achieve near-zero emissions from pulverized coal power plants. Furthermore, Visage Energy and SRI International are working together with several partners to develop membranes for pre-combustion based CO_2 capture. Despite the fact that 40% of the projects are capture projects, other capture clusters are not clearly visible in the network. This is mainly caused by the fact that capture projects are of smaller-scale and carried out by single parties or within bilateral partnerships. For example, Praxair is developing oxyfueling together with Alstom and the University of Utah in two separate R&D projects.[6] So the potential for information exchange in R&D of CO_2 capture technologies is rather small if you compare this to the knowledge that is obtained in storage projects, as the storage clusters are highly connected.

Table 3 summarizes the descriptive statistics of the network between 2000 and 2008. Over the years we observe a decrease in the number of components, i.e. disconnected parts of the network, and isolated actors. The size of the largest component increased significantly over time. This indicates that the innovation system is building up. In 2008, 176 actors are connected through the largest component, representing 89% of the total network. The observation from visual inspection that the network has become increasingly connected is confirmed by the mean degree of the network, which increases from 3.45 ties per actor at the end of the characterization phase (2005) to 6.4 at the end of the validation phase (2008). Meaning that more actors cooperate with each other in CCS projects and the potential for knowledge exchange has increased significantly. Furthermore, we find an (slightly) increasing clustering coefficient in the validation phase.[7] In combination with the increasing path length between actors this could indicate that peripheral actors in the network are becoming stronger connected with each other than to actors in the center. The decreasing cohesion in the network, but at the same time increasing connectivity between actors, can be interpreted as a stronger focus on core competencies in separate parts of the CCS chain. The latter can be explained by the fact that when an innovation system matures, groups of actors will look for a certain

[4] This restriction is only used for visualization of the network and implies that isolated actors, or isolated components (with less than 5 actors) are not displayed.

[5] Note that these projects are not part of the validation phase field tests depicted in Fig. 1.

[6] Note that Praxair obtains its central position in the network through its participation into large sequestration projects, like Frio Brine and PCORP's Lignite Field Validation test.

[7] The overall clustering coefficient is calculated by averaging the clustering coefficients of all actors within the network. The node level clustering coefficients are calculated as the density of the neighborhood, i.e. the network of actors directly linked to the respective actor [33].

Table 3
Descriptive statistics of CCS actor networks in the US between 2000 and 2008.

	2000	2001	2002	2003	2004	2005	2006	2007	2008
Actors	83	95	121	130	132	123	134	187	198
Number of components	6	6	6	7	8	8	5	4	4
Largest component	47	60	94	93	96	87	110	166	176
Isolates	8	13	19	22	19	18	16	12	8
Mean degree	4.27	4.01	4.44	4.18	4.13	3.65	4.00	5.50	6.41
SD mean degree	3.16	3.16	3.35	3.82	3.78	3.45	3.78	4.66	6.32
Clustering coefficient	0.95	0.94	0.95	0.96	0.94	0.94	0.92	0.96	1.01
Average path length	2.15	2.25	2.83	2.88	2.96	2.89	3.54	3.45	3.73

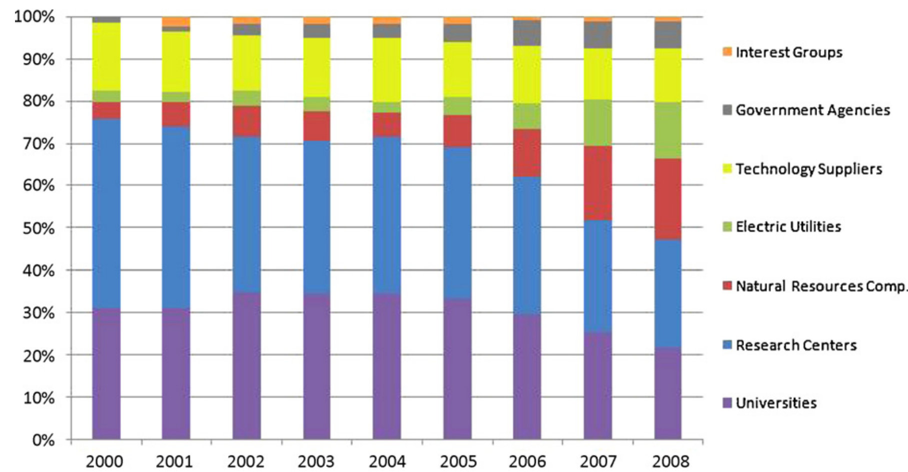


Fig. 3. Actor composition of CCS networks in the US between 2000 and 2008.

research or market niche and specialize in specific parts of the value chain.

Fig. 3 shows that several important shifts can be found in the composition of the network. First of all, we see a growing share of enterprises at the expense of research institutions and universities, indicating that the prominence of technology developers and energy companies is increasing over time. This change is mainly caused by the increasing involvement of oil, gas and coal companies. Also the relative amount of utilities has risen substantially, indicating an increased attention for capture technologies in recent years. The more prominent role of governmental actors in the network, like the EPA, can be explained by the need to resolve regulatory issues that are encountered when demonstrating the technology. These shifts in the actor composition of the CCS network in the US indicate a change from technological R&D towards demonstration and pre-commercialization for CCS.

4.3. Technological development, demonstration and diffusion

Fig. 4 shows an increasing amount of funding for CCS research and demonstration over the past decade. Total investments doubled from USD 20 million per year in the beginning of the millennium to USD 40 million in 2005. After that, investments in CCS rose to nearly USD 140 million in 2008. As can be derived from the figure, the steep increase in CCS investments is caused by the relatively large budget that is available for demonstration of CO_2 storage projects through DOE's Carbon Sequestration Program. In terms of storage most funds are allocated to demonstration projects in saline aquifers and hydrocarbon fields. The large investments in CO_2 storage projects related to saline formations can be explained by its large storage potential compared to other reservoir types [4]. Furthermore, considerable experience already exists in CO_2 storage into hydrocarbon fields, through the use of CO_2 for EOR.

Investments in aquifer storage projects will increase further in the near future with the commencement of the deployment phase of the Carbon Sequestration Program. So far, DOE awarded nine grants representing USD 511 million to the regional Partnerships to conduct large-scale field tests, including 8 tests in saline aquifers (see Table 4). Major investments into demonstration of CO_2 capture related to power generation are also expected through the US-DOE sponsored Clean Coal Power Initiative and FutureGen efforts.

The FutureGen Alliance, led by the coal-fueled electric power industry, intends to build a 275 MW coal-fired IGCC power plant with CCS in Mattoon, Illinois. However, in 2007 the costs for FutureGen nearly doubled to USD 1.7 billion and DOE decided in June 2008 to discontinue support for FutureGen and sponsor several smaller pilot projects instead. One year later, in June 2009, DOE reassessed that decision and reached agreement with the Alliance to complete a new preliminary design of the plant and a revised cost estimate. Early 2010 a decision will be made whether to move forward into the subsequent phases of the project. If the FutureGen continues, DOE anticipates committing 1 billion in funds under the American Recovery and Investment Act of 2009 [55]. The remainder of the USD 3.4 billion designated in the Recovery Act for CCS RD&D will finance other industrial-scale CO_2 capture installations at coal-fired power plants and oil refineries. Together with the funding available for early deployment of CCS under the ACES, this will provide a substantial impulse to the relatively low investments in CO_2 capture demonstration projects so far (see Fig. 4).

In summary can be said that driven by political ambitions, in little over a decade, CCS has changed from a concept of limited interest, to one that is widely regarded as an important option to mitigate climate change. Through the implementation of comprehensive CCS R&D programs and the formation of conducive CCS networks, CO_2 storage operations have advanced towards market

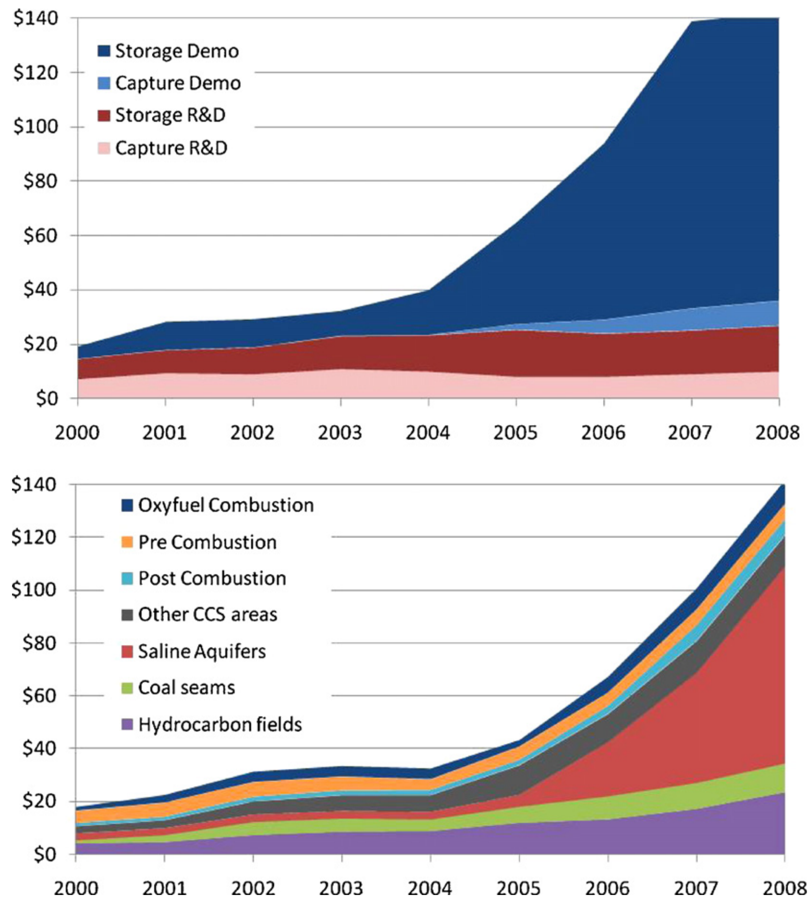


Fig. 4. Investments in CCS sub-technologies between 2000 and 2008.

maturity, while CO_2 capture technologies are still at brink of being demonstrated at scale.

5. Evaluation of innovation system performance

The patterns in structural growth of the US CCS innovation system show a consistent build-up of an innovation system around CCS technologies. This is visible through the increasing availability of funding; changes in legislation; entry of new actors; formation of strong CCS networks; and advancement of the technology. However, the current system structure does not guarantee a thriving development of CCS in the future. The US CCS innovation system may face challenges that obstruct a further expansion of the system. In order to identify these possible impediments, we use the concept of innovation system functions. In our theoretical framework we have shown that these functions make a suitable set of criteria for the performance assessment of an emerging innovation system. Therefore, the main actors composing the innovation system have been asked to reflect upon the ongoing activities regarding CCS and rate their level of satisfaction with the fulfillment of each of the seven system functions. All ratings are on a scale of 1–5, whereby 5 equals high level of satisfaction. Based on these expert judgments attributes of the current system structure that are driving, or blocking the future development of CCS technologies can be identified.

5.1. Function 1: entrepreneurial activities

Despite the growing amount of demonstration projects and the increasing share of industrial parties in the CCS network, the experts rated their satisfaction of the current fulfillment of this function with a 3.0, which indicates that on average their opinion is moderate. However the relatively high standard deviation (SD) of 1.4 specifies that there is no agreement on this score. The latter can be explained by the difference in technological advancement between capture and storage technologies. Most experts recognize that a significant amount of storage pilot-scale demonstration tests have been carried out, or are planned. Despite this, it is recognized that the variety in storage projects can still be improved. It is argued that even among deep saline formations there is a lot of heterogeneity and that more commercial-scale projects are necessary to improve monitoring techniques and to test the integrity of various reservoir types.

In contrast to storage projects, capture technologies are hardly tested at scale. The present high costs of CO_2 capture at power plants – i.e. USD 40–90 per tonne CO_2 captured [41][8] – is one of the main barriers to its application. Next to high prices for capture equipment, the energy penalty as well as the possible loss of availability of the power plant are important cost factors. It is argued that is too early to 'pick winners' and that all three-capture options – i.e. post-combustion, pre-combustion and oxy-combustion – should be demonstrated at pilot and commercial-scale first to advance technological learning and bring down the costs. Besides demonstrating capture facilities into new power plants, the experts point out that more efforts should be made to deploy retrofit options for existing power plants.

Next to demonstrating the different parts of the CCS chain separately, the experts agree on the necessity to implement large-

[8] The costs of CO_2 transportation and sequestrations are considerably lower – between USD 10–30/tCO_2 – depending on trade offs between injectivity and proximity [41].

Table 4
RCSPs deployment phase field projects as planned in 2009 [52].

Partnership	Location	Formation	Type	CO_2/year	CO_2 source	Start date
MGSC	Central Illinois	Mount Simon Sandstone	Saline	1 Mt	ADM ethanol facility	December 2009
MRCSP	Western Ohio	Mount Simon/Cincinnati Arch	Saline	1 Mt	TAME ethanol facility	March 2010
PCOR	North Dakota	Williston Basin Carbonate	EOR	1 MT	Basin Electric Antelope Station (post-combustion)	June 2012
PCOR	Fort Nelson (Alberta)	Alberta Basin Sandstone	Saline	4 Mt	Spectra gas processing plant	January 2011
SECARB	Gulf Coast	Tuscaloosa Sandstone	Saline	2.1 Mt	Jackson Dome CO_2 Pipeline/ Southern Comp. power plant	January 2009/Jun 2001
SWP	Central Utah	Franham Dome Sandstone	Saline	2 Mt	Farnham Dome natural deposit	March 2010
WestCarb	Kimberlina (California)	Olcese/Vedder Sandstone	Saline	1 Mt	Clean energy systems power plant (oxyfuel)	June 2012
BigSky	Western Wyoming	Moxa Arch Sandstone	Saline	1.5 Mt	Gas processing	January 2010

scale integrated CCS projects. Almost all experts referred on this subject to DOE's initial plans of restructuring the FutureGen project and equip multiple smaller-scale coal-fired power plants with CCS. Most of the experts that participated in this study see the original FutureGen as *the* integrated commercial-scale demonstration project that is crucial in the development of CCS. Therefore they would like to see that the FutureGen Alliance and US-DOE will make the decision to move forward with the project early in 2010.

Related to the issue of project integration is the lacking business interface between the producers of CO_2 – mainly power producers – and those who will be injecting it into the subsurface; mainly oil and gas companies. It is argued that the development of such an intermediary organization is of critical importance for the future success of CCS [5]. This role could be fulfilled by the CO_2 transportation companies, which can take care of both the physical as well as the contractual infrastructure between the CO_2 emitters and injectors. Finally, it was noted by many experts that besides investing in large-scale integrated CCS projects, more efforts should be made to 'pick the low hanging fruit' and start more low-cost CCS projects making use of CO_2 from relatively pure industrial CO_2 streams. In short, it is time that entrepreneurs really start 'learning by doing', instead of 'learning by planning'.

5.2. Function 2: knowledge development

Although the relative amount of research organizations in the network is decreasing and less new R&D projects started-up recently, experts are satisfied with the knowledge base that has been accumulated over the past decade. On average they scored this function with a 3.9 (SD: 0.8). The main driver behind the fulfillment of this function is the solid funding structure of DOE's Carbon Sequestration Program and the associated RCSPs. The NatCarb project was mentioned as one of the most remarkable R&D outputs of the RCSPs by most of the CCS experts that participated in this study. This joint R&D effort of the RCSPs resulted in an interactive database presenting all potential point sources and geological storage sites for CO_2 in the US and parts of Canada [3]. It is argued that this project has laid the foundation for the storage field tests that are currently carried out in the US.

The knowledge developed regarding storage options is considered as of high quality and sufficient. Some experts noted that more R&D is necessary to develop advanced monitoring techniques and to test the (long-term) integrity of reservoirs as well as CO_2 pipelines. Even though 3400 miles of CO_2 pipelines are already laid out in the US, it is argued that more research is needed to resolve regulatory, financing, siting and safety issues and help ensure that CCS-dedicated CO_2 pipelines are constructed. On the quality and diversity of capture R&D experts are less satisfied. More basic research into new solvents, sorbents and membranes is needed to identify innovative cost-effective capture technologies. Moreover, R&D efforts should diversify towards CO_2 capture related to gas fired generators and retrofit options for existing power plants. Finally, it was noted that more attention should be paid to developments in fuel cell technology as well as in commercial gasification processes, as these research areas offer considerable learning potential for the development pre-combustion CO_2 capture technology.

Despite the above, the most important stimulus for this function is the implementation of more demonstration projects to test the developed knowledge in commercial-scale experiments. So, it is hard to identify general impediments in the fulfillment of this function other than the need to move several technologies further up the innovation chain to enhance technological learning.

5.3. Function 3: knowledge diffusion

Considering the growth and increasing connectivity of the US CCS network over the past decade, it is no surprise that knowledge diffusion is, according to the experts, the best-developed function of the innovation system with a score of 4.2 (SD: 0.9). The most important drivers for knowledge diffusion are the open knowledge base, conferences, national and international collaborations and the formation of regional partnerships.

The interviewees are satisfied with the amount and quality of shared information in the increasing number of CCS conferences and workshops. The most well known conferences are the annual NETL-conference and the bi-annual International Greenhouse Gas Control Technologies (GHGT) conference series. The largest GHGT conference until now was held in Washington DC, in November 2008. The conference, which hosted nearly 1500 participants from 42 different countries, was organized by MIT in collaboration with the IEA GHG R&D Program, with major sponsorship from the US-DOE.

Next to their involvement in the IEA GHG program, the US-DOE is working with the Department of State in an international ministerial-level panel that discusses the growing body of scientific knowledge on CCS and plans joint projects. This Carbon Sequestration Leadership Forum (CSLF) involves the world's largest blocs of economic activity, including the North America Free Trade Area, the European Union and the leading economies of Asia. Many CSLF recognized projects are meant to identify and further quantify the potential of storage sites. At present, there are 20 projects that have received CSLF recognition, including the RCSPs, the Frio project and the IEA GHG Weyburn-Midale CO_2 Monitoring and Sequestration Project [56]. Other global CCS initiatives that involve American organizations and receive funding through the US-DOE are the GEOSINK project in Ketzin, Germany; the In Salah gas project in Algeria; and the Otway Basin project in Australia [48]. New activities include the first projects in developing nations – two in China and one in India. This is in line

with the experts' view that more should be done to develop a complementary set of CCS demonstration projects around the world, including rapidly growing coal-using countries in Asia. An objective that is also strived after by the US led Asia-Pacific Partnership on Clean Development and Climate. This partnership aims to accelerate the development and deployment of clean energy technologies, including CCS.

In terms of national CCS collaborations, the RCSPs fulfill a crucial role in facilitating the exchange of knowledge within CCS networks. Best practices have been made available in order to optimize technological learning. However, several interviewees note that this is mainly true for parties involved in storage projects and less for organizations that develop capture technologies. This is confirmed by the result of our network analysis, which shows a relatively high amount of actors involved in CO_2 storage projects in the centre of the network. The experts argue that some R&D of capture technologies occurs behind 'closed doors' and that the protection of intellectual property hinders an optimal flow of knowledge between the actors. This is mentioned as the most important barrier for the performance of this functions and has to be overcome before integrated projects in CCS can be carried out.

5.4. Function 4: guidance

On average, the experts rated their satisfaction of this function with a moderate score of 3.2 (SD: 0.9). They are satisfied with the clarity of technological demands articulated by industry towards scientific organizations; the developments in targets and regulations on state and national level, as well as the role of political leaders in advocating the promise of CCS. As part of his "New Energy for America" plan, President Obama wants to develop and deploy CCS as it provides an opportunity to create green jobs. At his website the President states that "the US-DOE will enter into public private partnerships to develop five first-of-a-kind commercial-scale coal-fired plants with clean CCS technology" [57]. This would be a quarter of the 20 worldwide CCS demonstration projects the G8 called for by 2020 [58].

Even though these envisioned technological trajectories have been documented in several influential Roadmaps (see, e.g. NETL [51]), it is argued that the industry is not going to invest in CCS unless they can rely on an unambiguous regulatory framework supporting CCS. Such a framework would not only include clear climate policy (which we will discuss further under the next function: 'market creation'), but also legislative solutions related to standardization, permitting and liability. There is wide agreement among experts that permitting capture and transportation facilities are not substantially different than for conventional industrial facilities. However, it is anticipated that CO_2 injection can only be partly covered by existing Federal and State legislation on CO_2 for EOR, natural gas storage and acid gas disposal, and that a new set of rules is needed for underground injection and storage of CO_2. The experts argued that additional legislation is most needed with regard to pore space ownership and its interaction with mineral rights, as well as long-term liability, in case CO_2 leakage from the reservoir causes damage to humans or the environment.[9]

As mentioned in paragraph 4.1, the ACES Act of 2009 establishes regulations for geological CO_2 storage. The Bill Amends the Clean Air Act and Safe Drinking Water Act to establish rules for geologic storage, including financial responsibility for injected CO_2, monitoring, record keeping, public participation and certification for storage sites. Furthermore, the bill establishes a task force to provide recommendations to Congress before 2012 that include a study of the ability of existing laws and insurance mechanisms to deal with subsurface property rights and to manage risks associated with CCS, including implications and considerations for different models for liability assumption [47].

So, there is strong visionary guidance from political leaders, industry captains and influential scientists regarding the promise of CCS as a low-emission bridge towards a sustainable energy future. Moreover, signs are that regulation and standards that will enable safe and effective injection of CO_2 for the purposes of storage are within close reach. However, more clear legislation is still needed regarding liability and ownership of the sequestered CO_2.

5.5. Function 5: market creation

From the analysis of the innovation system structure, we know that since the year 2000, CCS technologies have advanced from a science-based technology to an option, of which its separate parts are widely demonstrated by industry. For example, in niche applications such as EOR, whereby relative inexpensive CO_2 from particular industrial operations is utilized to gain extra oil revenues. However, it is unlikely that utilities will adopt CCS on a large-scale until sound climate policies make CO_2 financially worth capturing. It is argued that the main barrier that has been standing in the way for the uptake for integrated commercial-scale CCS projects related to power generation is the absence of a clear regulatory framework that create economic drivers for CCS. The interviewees agreed almost unanimously on this point and therefore rated the fulfillment of this function as weak: score 2.0 (SD: 1.0).

On state level, several initiatives are taken that vary between being committed to reduce GHGs to a multi-state cap-and-trade system. Experts do appreciate these efforts, but they would like to see a federal regulation. The approved ACES Act (H.R. 2545) by the House of Representatives can therefore be seen as a major breakthrough for the creation of a market for CCS. Starting in 2012, ACES establishes annual tonnage limits on CO_2 emissions from large US sources such as electric utilities and oil refineries. Under these caps, GHG emissions must be reduced by 17% by 2020 and 83% by 2050 compared to 2005 levels. To achieve these targets, ACES establishes a cap-and-trade system wherein emission allowances can be traded between participants. This market-based approach provides economic incentives for industry to reduce CO_2 emissions at lowest cost.

Next to introducing electric renewable standards, that require electricity suppliers to produce 20% of its electricity from renewable sources by 2020, ACES uses a combination of regulatory requirements and financial incentives to ensure that new fossil fuel based power plants will operate with CCS technology. ACES requires all new coal plants with a capacity of 250MW or greater that receive permits from 2009 to 2014 to emit no more than 500 kgCO_2/MWh no later than 2025 and potentially earlier depending on the level of commercial deployment of CCS technologies. Plants permitted from 2015 to 2019 must emit less than 500 kgCO_2/MWh at the start. The EPS for new coal-fired power plants commencing after 2020 is set at 365 kg/MWh. Taking into account that the CO_2 emissions of a pulverized coal (PC) plant ranges from 736 to 811 kg/MWh and for an IGCC from 682 to 846 kg/MWh [61], implies that the only way to comply with the standards is to use CCS.

In order to offset the financial burden for power producers and industries that need to apply CCS in their daily operations, the ACES Act sets aside bonus allowances to support commercial deployment of CCS [48]. Up to 6 GW of CCS may receive a subsidy of USD 90 per tonne of captured CO_2 for 10 years. Additional allowances are available through a reverse auction, allowing much of the additional CCS projects to receive subsidies greater than USD 50/tCO_2.

In addition to the bonus allowances, ACES establishes a Carbon Storage Research Corporation to be run by the Electric Power

[9] See Duncan et al. [59] and Wilson et al. [60] for more information on these outstanding regulatory issues.

Research Institute. The Corporation would use funds collected through levy on fossil fuel based electricity[10] to issue grants and financial assistance for at least 5 early commercial-scale CCS demonstrations. The importance of financing the first large-scale CCS demonstration projects in order to proof the concept of CCS and lower its costs has been noted by most of the interviewees. They argued that besides creating a clear market for CCS, it is of prime importance that the technology becomes 'market ready'.

5.6. Function 6: mobilization of resources

Although investments in CCS have grown substantially over the past decade to a level of roughly USD 140 million in 2008, experts rate their satisfaction on the availability resources with a score of 2.8 (SD: 1.1). Their opinion is that the current availability of financial resources is not sufficient to realize commercial-scale integrated CCS demonstration projects. Taking into account that the carbon price (if there is going to be one) in the early years might not be high or stable enough to trigger enough CCS investment, additional incentives will be needed.

With the half a billion dollar DOE funding for the deployment phase of the Carbon Sequestration Program, several of the regional partnerships have started ambitious collaborations with power generators (see also Section 4.3, Table 4). The largest project so far would capture up to 1 $MtCO_2$ annually from the Antelope Valley Station in North Dakota and is expected to start operation in 2012. The US-DOE sponsors USD 100 million of the project investment costs and the Department of Agriculture has offered USD 300 million in loans to the project developers, which will partly be paid back by the extra revenue generated from CO_2 EOR operations [62].

In February 2009, a financial boost for CCS came from the US government's Recovery Act funds for CCS research and demonstration. Much of the USD 3.4 billion designated for fossil fuel R&D – about five times what the DOE now spends annually on such research – will finance commercial-scale CO_2 capture installations at coal-fired power plants and oil refineries. However, Secretary of Energy Steven Chu said shortly after the announcement of the funds: "It sounds like a lot of money, but it doesn't go that far..." Thereby he referred to the FutureGen project, which price tag rose to USD 1.7 billion [63].

The DOE approach requires large investments from industry, while the current trend is showing the opposite; industry is reluctant to invest in CCS as they await carbon policies. In order to provide investor certainty, it is believed that the most appropriate form would be a direct cash subsidy for commercial-scale CCS projects whose level declines as cumulative deployment increases. According to the experts, this approach would offer the highest incentives to early projects that have not yet benefited from scale economies and technological learning.

In contrast to the availability of financial capital, it is argued that there is enough trained and educated personnel that can work in the field of CCS. However, the experts are a little worried about the availability of human capital in the future, as CCS has the potential to become an industrial sector that is comparable to the current oil and gas industry. Especially if you take into account that current petroleum-engineering departments are already operating up or above capacity [64]. Experts see the solution for this potential problem to introduce educational programs at universities to get future engineers acquainted with specific CCS knowledge.

5.7. Function 7: creation of legitimacy

The current fulfillment of this function is scored 2.9. Although moderate, the creation of legitimacy is a somewhat difficult function in the US CCS innovation system. The legitimacy for CCS is different for each of the stakeholders, ranging from politicians, coal lobby groups and communities that are encountered with storage projects under their back yards. This is one of the reasons that the scores on this function diverge from 1 to 5 causing a relatively high standard deviation of 1.4.

As politicians embrace CCS as one of the options in a broad mitigation portfolio, necessary to reach their climate ambitions, and the fossil fuel industries see CCS as an opportunity to stay in business in a low carbon economy, the major bottleneck in the fulfillment of this function lies in possible public resistance towards the technology. Even thought the fast majority of the US citizens are not familiar with the concept of CCS, the issue of public perception is regarded as very important for the future deployment of the technology [65]. It is argued by the experts that a public backlash against the technology in general, or in opposition towards the siting of a specific project, can stall the development of CCS by many years.

CCS is often portrayed as an experimental technology by skeptics, and as a lifeline for the continued use of coal and other fossil fuels that detracts from efforts to shift to a truly sustainable energy system.[11] Furthermore, local communities living close to a geological storage site are concerned with the risks involved with CO_2 transportation, injection and storage. Even though CO_2 is a normal constituent of the atmosphere and safely used in a variety of industrial applications (e.g. food preservation), CO_2 is dangerous to humans at ambient concentrations greater than about 3%, and must be safely managed in order to avoid such concentrations. Many experts, including the US EPA, have argued that a rapid release of injected CO_2, which could lead to such concentrations, is unlikely because of the physical characteristics of geologic confining units [53]. Yet the perceived risk of such a release is significant.

In relation to the issue of risk perception, the interviewees often referred to BP's Carson project in California. Early 2006, BP and the Edison Mission Group announced their plans to build a USD 1 billion petroleum coke fueled power plant in California with a minimum of CO_2 emissions. Despite the fact that BP conducted outreach for 2 years – briefing more than 300 people including federal, state and local officials, community leaders and environmental organizations [67] – local environment groups seized on the project as a rallying point for their opposition to a State bill designed to set standards for CCS. In April 2007, ten environmental justice groups protested to the project, saying "CO_2 releases are deadly for communities".[12]

This example points out that in order to increase public support, more should be done to engage the public and environmental NGOs in the siting of CCS projects. Thereby it is of prime importance to pay attention to the significant body of literature that is available on public perception of CCS (see Ashworth et al. [68] for an overview) and to take advantage of successful public outreach strategies applied in other CCS projects, like FutureGen [69]. It is argued that (risk) communication on CCS cannot start early enough and that without public engagement, CCS projects risk being unsiteable. Therefore, some of the interviewees note that experts should engage more often in open dialogue with the public about benefits, risks and other legitimate concerns about CCS. Any communication on CCS needs to be in the context of climate

[10] Rates are set at 0.043 dollar cent for coal based electricity, 0.022 cents for natural gas and 0.032 cents for oil [47].

[11] See for example the short movie 'Get clean coal clean: a new air refreshner' by the directors Joel and Ethan Coen, wherein they proclaim that the idea of "clean coal" is, at least for now, nonsense [66].

[12] A year later, the project was relocated in close proximity to the Elk Hills oil field in rural Kern County. According to BP the opportunities for EOR where better at this new location. Furthermore this project received USD 308 million funding from DOE Clean Coal Power Initiative in June 2009 [62].

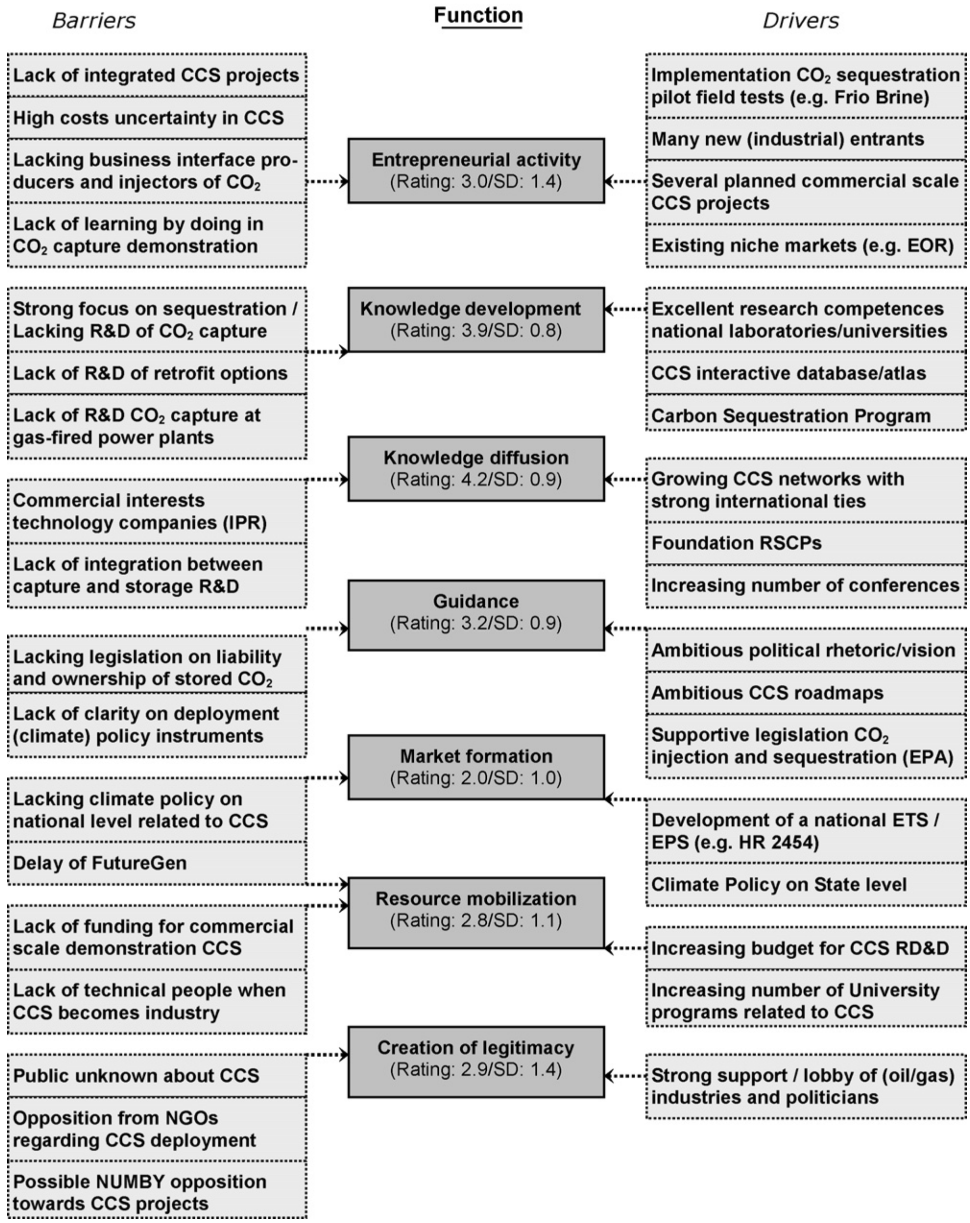


Fig. 5. Drivers and barriers for CCS development and deployment in the US.

change, namely CCS as part of a portfolio of mitigation options and not at the expense of renewables.

6. System intervention: implications for policy

In order to improve the performance of the innovation system and accelerate the deployment of more advanced CCS concepts in the US, it is necessary to direct policy initiatives at the structural attributes of the system that drive or block a fulfillment of a particular system function (see Fig. 5). Below we will discuss a policy strategy that would stimulate a thriving development of CCS in the US. This strategy consists of four integrated elements that target different sets of system functions, namely (1) stimulate learning by doing; (2) facilitate coordination and collaboration; (3) create financial and market incentives; and (4) regulate and communicate.

6.1. Stimulate learning by doing (functions 1 and 2)

The performance assessment of the US CCS innovation system shows that the extensive knowledge base and CCS knowledge networks, accumulated over the past years, have not yet been valorized by entrepreneurs to explore markets for CO_2 capture concepts linked to power generation. In contrast to storage projects, capture technologies are hardly tested at scale. It is argued that besides continuing laboratory R&D of innovative capture techniques and retrofit options, various promising technologies should be demonstrated at commercial-scale to advance technological learning and bring down its costs. Furthermore, it is of prime importance that, besides demonstrating the different parts of the CCS chain separately, a number of integrated large-scale CCS projects are implemented in order to prove the concept.

In contrast to the relatively slow technological advancements in the capture part of the CCS chain, a significant amount of storage field tests have been carried out, or are planned. Despite this, it is recognized that variety among storage projects can still be improved, as more work is needed to advance and commercialize monitoring techniques. This can be done by starting up more low-cost CCS projects that make use of CO_2 from relatively pure industrial CO_2 streams, e.g. refineries and natural gas processing. In

short, it is time that entrepreneurs really start learning by doing, instead of 'learning by planning'.

6.2. Facilitate coordination and collaboration (function 3)

To facilitate the development of integrated CCS demonstration projects changes in (inter)national collaborative networks are necessary. Despite the growth and the increasing connectivity within the network of actors that are involved in CCS in the US, we see a stronger focus on core competences in separate parts of the CCS value chain. Furthermore, it is recognized that now CCS technologies are maturing, the protection of intellectual property hinders an optimal flow of knowledge between organizations. In order to solve IP issues, integrate the CCS chain, and take optimal advantage of the available learning potential, coordinated action is necessary. More should be done to develop a complementary set of CCS demonstration projects in the US, but also internationally, including rapidly growing coal-using economies like China and India.

Demonstration projects should be designed to maximize and accelerate technological learning by integrating different individual components of a complete CCS system, and enabling transparency of knowledge that would otherwise remain hidden. With the introduction of intermediary organizations, best practices could be made available in order to gain potential cost reductions and ensure consistency in safety and integrity of CCS projects. Such a coordinating body does not necessarily have to be a governmental agency, but might as well be a private enterprise, as there is a lacking business interface between the producers of CO_2, like utilities, and those who will be injecting it into the subsurface, mainly oil and gas companies.

6.3. Create financial and market incentives (functions 5 and 6)

The implementation of sound climate policies and legislation is vital for the development of commercial-scale CCS projects, as strong economic drivers for CCS are currently lacking. The industrial sectors that may apply CCS in their daily operations should be able to rely on a long-lasting change in the institutional infrastructure of the innovation system that creates a clear market for CCS. The temporal subsidies and tax credits that have been applied so far are a necessary first step, but do not seem to be strong enough to deal with the relatively high (investment) costs of power generation with CCS. Therefore, it is necessary that the federal government changes 'the rules of the game'. It is believed that the proposed nation wide cap-and-trade system – with bonus allowances for CCS projects – in combination with EPS' for generators could be a strong policy mechanism to create a market for CCS on the mid and longer term.

However, taking into account that the carbon price in the early years might not be high or stable enough to trigger enough CCS investment, additional incentives will be needed. It is argued that public private partnerships are the way to go in establishing early commercial-scale CCS demonstration projects. Government agencies can provide investor certainty by funding a substantial part of the billions of dollars necessary to deploy the first set of integrated CCS projects. The level of public financing than declines as cumulative deployment increases. Such a direct subsidy scheme would offer the highest incentives to early projects that have not yet benefited from scale economies, technological improvement and learning.

The foundation of a Carbon Storage Research Corporation, as proposed under the ECAS Act of 2009, provides opportunities to create the necessary financial assistance to implement the first set of integrated CCS projects and the construction of a CO_2 pipeline infrastructure. For now, substantial funds for CCS demonstration have become available through the US government's economic stimulus package. Although essential, we would argue that such investments are futile in the absence of an overarching long-term climate policy. Sound alteration of short-term financial incentives to stimulate learning by doing and long-term market incentives is therefore of prime importance to accelerate the deployment CCS in the US.

6.4. Regulate and communicate (functions 4 and 7)

Over the past decade CCS has become an important consideration in US climate policy discussions and political rhetoric. In order to give meaning to their ambitious discourse, political and industrial leaders can foster the implementation of CCS technologies by providing clarity on the set of policy instruments that will be used to meet their ambitions. Such a regulatory framework is not limited to clear climate policies and financial incentives, like the ECAS Act, but should also include regulation and standards that will enable safe and effective CCS projects.

Several states are actively pursuing CCS through implementing environmental regulations. Furthermore, the US EPA already proposed regulation for commercial-scale CO_2 storage that will include standards for site characterization, well construction and operation, monitoring and post-closure care. However, there are some questions that the proposed legislation leaves unanswered. Notably, legal issues around pore space ownership and its interaction with mineral rights, as well as long-term liability for possible environmental damages in case the CO_2 might leak from the reservoir. Regulatory agencies should therefore provide approvals on a 'one-time' basis to allow the first projects to move ahead; then they should use the subsequent learning to write the rules for broader application of future CCS projects.

A strong regulatory framework could minimize concerns of CCS being a 'risky technology', thereby building public trust in CCS applications. It is clear that without enough support from a broad coalition, the development of the technology may suffer from resistance. Therefore, such a regulation should include mechanisms to support CCS projects that engage a wide range stakeholders and incorporate public outreach efforts. It is argued that an open two-way communication with stakeholders, including (environmental) interest groups, the media and members of the local community should be an integral of CCS projects. Thereby it is of prime importance to take advantage of successful public outreach strategies applied in other CCS projects. Any communication on CCS needs to be in the context of climate change and portray CCS as part of a broader portfolio of climate mitigation options, including renewable and energy efficiency measures.

7. Discussion

The analysis of the historical growth of the US CCS innovation system and the evaluation of its current performance have resulted in a policy strategy that may accelerate the deployment of CCS in the US. However, when implementing a specific set of policy instruments one should also take into account the possible effects on the development of other (competing) sustainable energy technologies and vice versa. Moreover, it might be possible that new and more influential innovation system dynamics start off as part of developments in other countries. Due to the extensive international relationships in this technological field, a policy maker at the national level should be aware of the increasing importance of these global innovation processes for local activities. In order to analyze these global trends in the development of CCS technologies, it is desirable to apply the analytical framework presented in this study to other countries as well. These analyses would not only allow for cross-national comparison on a function

level – e.g. differences between R&D expenditures, technological focus, or market incentives – but would also provide an opportunity to learn from other countries in overcoming the obstacles encountered in the development of CCS technologies (see van Alphen et al. [70]).

Furthermore, this study focuses on a wide variety of aspects that are decisive for successful CCS deployment in order to formulate an overall policy framework. Although this is one of the strengths of taking an innovation system perspective, one should not neglect the in depth studies that focus on a single aspect of technology development. See for example, Groenenberg and de Coninck [71] on policies related to the creation of a market for CCS in Europe; Pollak and Wilson [54] on providing regulatory guidance for CCS in the US; Ashworth et al. [68] regarding legitimacy and public acceptance of CCS; or de Coninck et al. [72] on knowledge diffusion and global technological learning. We would argue that these in depth studies could fill in the guiding policy strategy that is sketched in this study.

Despite the technological and geographical delineations applied in this study, the results contain important insights in the dynamics and performance of the US CCS innovation system and identified several key policy issues that need to be addressed in order to stimulate the further growth of the system. These insights are not only of specific use for policy decisions regarding the deployment of CCS in the US, but can also be of value for decision makers in other countries that wish to accelerate the development of CCS.

8. Concluding remarks

The analysis of the US CCS innovation system provides insights into the relations between the historical growth of the system and the system's current performance. The results show a remarkable consistent build-up of a national CCS innovation system. Throughout the evolution of the system, conditions have been supportive for this to happen. Converging perspectives on the importance of CCS in the energy system by researchers, (industrial) entrepreneurs, and governments have resulted in a steady growth of the innovation system as a whole. This is visible through the entry of new actors in the system; extension of the knowledge base; increasing connectivity in CCS networks; successful entrepreneurial projects; increasing availability of public and private funding into CCS; changes in legislation; creation of strong advocacy coalitions; and a guiding government fostering the development of CCS.

The build-up of a well-performing CCS innovation system has given the US an international leadership position in the field of CCS. However, it is realized by the experts participating in the study that America's leading role in the development of CCS should not be taken for granted. Their evaluation shows that the extensive knowledge base and knowledge networks, which have been accumulated over the past years, have not yet been valorized by entrepreneurs to explore the market for integrated CCS concepts linked to power generation. It is recognized that CO_2 storage operations have advanced towards market maturity, while CO_2 capture technologies are still at brink of being demonstrated at scale. Therefore, it is argued that the build-up of the innovation system has entered a critical phase that is decisive for a further thriving development of CCS in the US. The evaluation of the current innovation system performance identified several barriers that block continuing positive system dynamics and stress the need for an integrated strategy that would target malfunctioning of the innovation system.

The proposed policy strategy consists of four main elements, namely (1) stimulate learning by doing; (2) facilitate integration and collaboration; (3) create financial and market incentives; and (4) regulate and communicate. In order to provide investor certainty in the near future, it is believed that the most appropriate form would be public private partnerships combined with a direct subsidy for a wide variety of commercial-scale integrated CCS projects whose level declines as cumulative deployment increases. The creation of such public private partnerships would offer the highest incentives to early projects that have not yet benefited from scale economies and technological improvement. In order to bring down the costs of the (first) projects and advance technological learning in commercial-scale CCS applications, (international) cooperation and knowledge exchange is of prime importance. Such a collaborative effort should not be limited to the development of a complementary set of roadmaps and demonstration projects, but also target regulation and standards that will enable safe and effective CCS projects. Clear legislation regarding site selection, safety standards, monitoring, ownership and liability are not only crucial for project developers, but also help to gain public trust in the technology. Open and effective two-way communication with stakeholders, the media and the general public about benefits, risks and other legitimate concerns should be an integral part of every CCS project plan. Although necessary, we would argue that all these efforts are futile in the absence of overarching long-term climate policies such as the ACES Act of 2009. It is necessary that the federal government changes 'the rules of the game' by implementing a nation wide cap-and-trade system – possibly with bonus allowances for CCS projects – in combination with EPS' for generators. Sound alteration of short-term financial incentives to stimulate learning by doing and long-term market incentives is key in the development and commercialization of CCS technologies in the US.

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